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Analyses of RC columns in a variety of sizes

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Abstract

Large-scale RC column tests have been performed in Japan at both the E-defense and JR-Tokai test facility and in United States at the University of California, San Diego Large Outdoor Shake Table Testing Facility. Such recent large-scale RC column tests have been compared with results of small-scale RC column tests. As a result, results of these large-scale model experiments show shortcomings in small-scale model experiments. At least one study showed that the small-scale model does not reproduce the observed damage on the large-scale model. Therefore, in order to develop small-scale model experiment results, experiment tests of small-scale model which might agree well with large-scale model should be undertaken. In an authors' previous study, experimental cyclic loading study on 0.1- and 0.2-scale RC column models was carried out and results have been compared with full- and 0.5-scale RC column models performed in the JR-Tokai test facility. Although the authors' experimental study clearly shows agreements and differences between large-scale model and small-scale model, the results still remain to be validated with respect to bond behavior between longitudinal steel bars and concrete. This study analyses full-, 0.5-, 0.2-, and 0.1-scale RC columns models using fiber model analyses to investigate the bond behavior analytically. This analytical study focuses on differences in hysteresis curves. Validity of the analysis results was determined by comparing experimental results of full- and 0.5-scale model. It is shown that fiber model analysis results agree well with the full- and 0.5-scale model. Although results of 0.1-scale models, which are scaled correctly for not only steel bar radius but also steel bar ribs, are capable to full- and 0.5scale model, analytical results of 0.2- and 0.1-scale model with different steel bar ribs seem to be less agreements. Therefore, it is shown that one of the causes of shortcomings in small-scale models is the difference of bond behavior between longitudinal steel bars and concrete.

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Keywords: Fiber model; hysteresis curve; bond behavior; RC column.

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1. Introduction

Large-scale RC column tests have been performed in Japan at both the E-defense [1,2] and JR-Tokai test facility [3] and in United States at the University of California, San Diego Large Outdoor Shake Table Testing Facility [4]. Such recent large-scale RC column tests have been compared with results of small-scale RC column tests [1-3]. As a result, those large-scaled model experiment results show shortcomings in small-scale model experiments. At least one study showed that small-scale model does not reproduce the observed damage on the large-scale model. Therefore, in order to develop small-scale model experiment results, small-scale model experimental tests which might agree well with large-scale model should be undertaken.

In an authors' previous study [5], experimental cyclic loading study on 0.1- and 0.2-scale RC column models was carried out, and results have been compared with full- and 0.5-scale RC column models performed in the JR-Tokai test facility [3]. Hysteresis curves until 4 δy of two 0.2-scale models which were made by both concrete and mortar do not have obvious differences in the both models, and therefore influence of aggregates is not significant until 4 δy. However, in addition to influence, the hysteresis curves of the two 0.2-scale models, whose radius of longitudinal steel bars is scaled correctly but steel bar ribs are not scaled, seem to be less agreement with full- and 0.2-scale models. In contrast, experimental results of the 0.1-scale models, whose radius of steel bar and ribs of steel bars were scaled up to the full-scale models, agree well with the full-scale model. Therefore, it may be concluded that differences of bond behavior between longitudinal steel bars and concrete result in less agreement of 0.2-scale models with large-scale models.

This paper shows analysis results of full-, 0.5-, 0.2-, and 0.1-scale RC column models using fiber model analyses. This analytical study focuses on differences in hysteresis curves to investigate bond behavior analytically. A common assumption in the analysis of RC column using fiber model is perfect bond between longitudinal steel bars and core and cover concrete, and therefore this analysis can capture the bond behavior if the RC column models can behave the perfect bond. In other words, although this analysis cannot capture the bond behavior that is not the perfect bond, this analysis might capture differences between the perfect bond behavior and other bond behavior when the RC column model may behave different bond behavior

2. 0.1- , 0.2-Scale RC Column Models Experiment [5]

The geometry of the scale-models which were analyzed in this study are shown in Fig. 1 and summarized in Table 1. This experimental work was carried out in author's previous study [5]. The column height of 0.2-scale model is 1350 mm with a diameter of 400 mm, which are with the scale factor of 0.2. The column height of 0.1-scale model is 650 mm with a diameter of 200 mm, which are with the scale factor of 0.1. Fig. 2 shows experiment set-up of the models. The 0.2-scale model was set up to a reaction wall horizontally and one jack was used for horizontal loading and two jacks were used for axial loading which were set up next to the models. The 0.1-scale model was fixed at footing and two jacks used for horizontal loading and axial loading, respectively (Fig. 2. (b)).

0.2-scale models used concrete and mortar to investigate influence of aggregates. An average of compressive strength of concrete and mortar used in 0.2- and 0.1-scaled model was approximately 30 N/mm^2 [5]. For 0.2-scale models, D6 longitudinal steel bars used for Type 1 and Type 2 in order to scale their radius correctly. For 0.1-scale models, D3 and D4 longitudinal steel bars used for Type 3 and Type 4, respectively. Longitudinal reinforcement ratio of Type 3 is scaled correctly, but the radius of D6 longitudinal steel bars for Type 3 is not scaled. Fig. 3 shows rib shapes of D6 and D3 longitudinal steel bars used in this study. As shown in Fig. 3, D6 has spiral rib shape (Fig. 3. (a)) and D3 has normal rib shape (Fig. 3. (b)). Therefore, differences of rib shape may result in different bond behavior between them. Based on tensile tests, yield strength, σ_y, and tensile strength, σ_T, of D6 and D3 are 456.2 N/mm^2, 588.3 N/mm^2 and 349.0 N/mm^2, 421.6 N/mm^2. A displacement-controlled testing on the horizontal direction with an axial load was conducted with the loading history, shown in Fig. 4, which was applied to the models.

According to axial load of the full-scale (1565 kN), axial load of the 0.2-, 0.1-scale models was 60 kN and 15 kN to be scaled based on a scale factor for force (Table 2). Prior to experimental tests, yield displacement δ_y was obtained from fiber model analysis instead of strain measurement on models because it is difficult to ensure an accuracy of strain measurement of D3 and D6 longitudinal steel bars which have small radius or spiral ribs. Yield strength, P_y, was obtained from experimental test when yield displacement δ_y applied to the models.

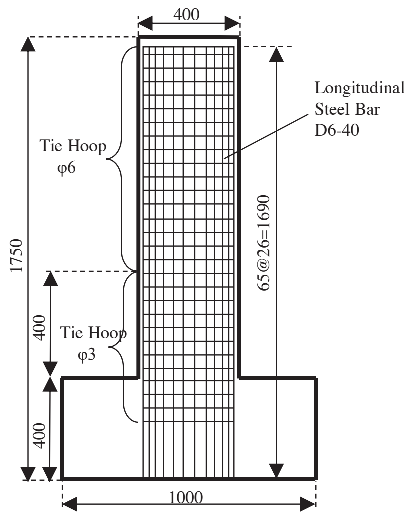

Fig. 1. 0.2- and 0.1-Scale RC Column Models [5]

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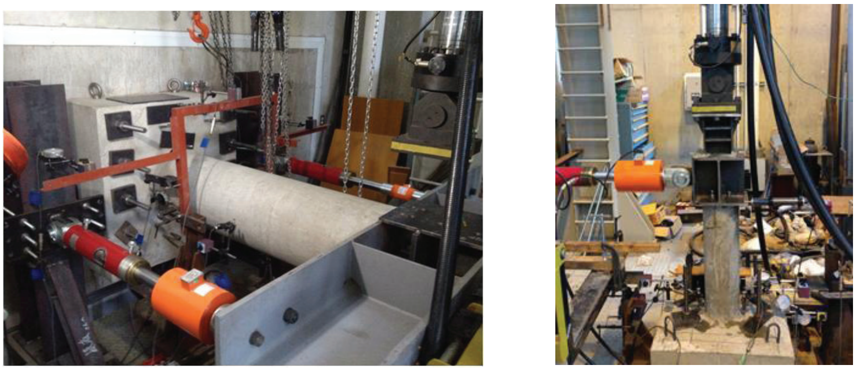


(a) 0.2-Scale Model (b) 0.1-Scale Model

Fig. 2. Experiment set-up [5]

(a) Spiral Ribs (D6)

(b) Normal Ribs (D3)

Fig. 3. Steel Bar Ribs

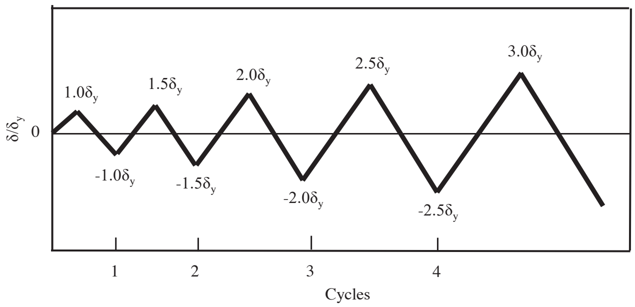


Fig. 4. Displacement Controlled Testing

Table 1. A List of Scaled Models

Type	1	2	3	4
Scale	0.2-Scale	0.2-Scale	0.1-Scale	0.1-Scale
Material	Concrete	Mortar	Mortar	Mortar
Longitudinal Steel Bar	D6	D6	D3	D6

Table 2. Scale Factors

Parameter	Symbol	Scale Factor		
Length	L	0.5	0.2	0.1
Density	ρ	1	1	1
Stress	σ	1	1	1
Mass	$M = \rho L^3$	$(0.5)^3$	$(0.2)^3$	$(0.1)^3$
Acceleration	$a = L/T^2$	2	5	10
Force	$f = \sigma L^2$	$(0.5)^2$	$(0.2)^2$	$(0.1)^2$
Strain	ε	1	1	1

3. Fiber Modeling of RC Columns

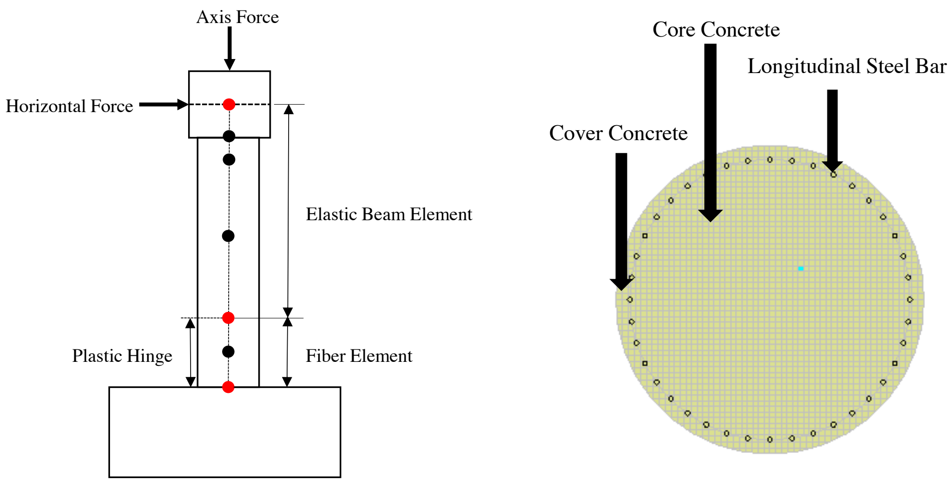
Fig. 5 shows analytical model using fiber element and a section of fiber element. A model is idealized as a single fiber element that has fine fiber division in the section. The models are divided into plastic hinge area and elastic area, and therefore elastic beam elements used in sections except the plastic hinge area [6]. The plastic hinge area was determined based on Specifications for Highway Bridges [7]. The stress-strain curves of core and cover concrete are shown in Fig. 6. The stress-strain curves of core concrete and unloading and reloading hysteresis of concrete were evaluated based on Hoshikuma et al. [8] model and Sakai and Kawashima [9] model. Compressive strength of concrete is assumed as 30 N/mm^2, which corresponds to the compressive tests of concrete and mortar. Residual compressive strength of concrete is 4 % of the compressive strength [10]. A bi-linear stress-strain curves with post yield stiffness, which is assumed as 1 % of the Young's Modulus of longitudinal steel bars, was used to model longitudinal steel bars, as shown in Fig. 7. The yield strength, σ_y, of D6 and D3 longitudinal steel bars is assumed as 456.2 N/mm^2 and 349.0 N/mm^2 , which corresponds to the experimental tests.

4. Analysis Results

Analysis results from the fiber model are presented in terms of strength and deformation. These results include strength, displacement and energy absorption. Energy absorption can be observed from shape or size of hysteresis curves. Validity of modeling was determined by comparing with the experimental results as the baseline.

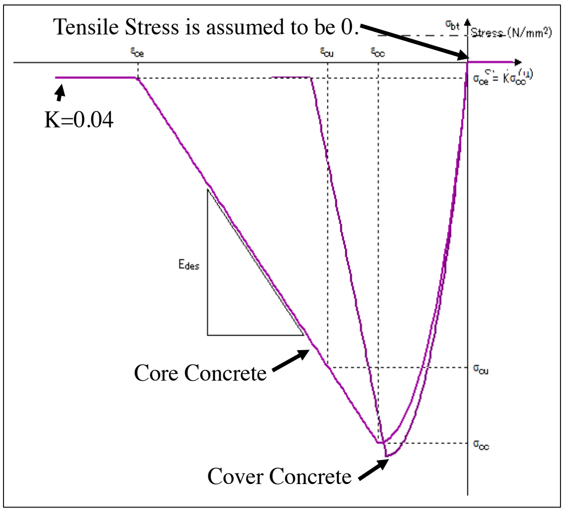
Fig. 8 and Fig. 9 show comparisons between experiment results and analysis results. Fig. 8 shows analysis results of $\pm 2.0\delta_y$ cycle and Fig. 9 shows $\pm 4.0\delta_y$ cycle used for the comparisons with experiment results. As shown in Figs. 8 (a), (b) and Figs. 9 (a), (b), analysis results agree well with experiment results of the full- and 0.5-scale model. Therefore, the fiber analysis of full- and 0.5-scale models is validated and it can be said that full- and 0.5- scale model may behave the perfect bond between longitudinal steel bars and concrete.

Fig. 8 (c), (d) and Fig. 9 (c), (d) show hysteresis curves of Type 1 and Type 2 of 0.2-scale models, whose longitudinal steel bars are D6. As shown in Figs. 8 (c), (d) and Figs. 9 (c), (d), although the analytical results are comparable in hysteresis curves with experiment results, the discrepancy in this relationship is observed. It is seen that the shape of hysteresis curves of the 0.2-scale shows narrow loops in the experiment compared to the analysis results, and therefore the analysis results of 0.2-scale models overestimate energy absorption. This overestimation shows clear differences between analysis results and experiment results, and it may be concluded that this is due to the use of assumption of the perfect bond between longitudinal steel bars and concrete.



(a) Analytical Model (b) Fiber Element Section

Fig. 5. Fiber Model



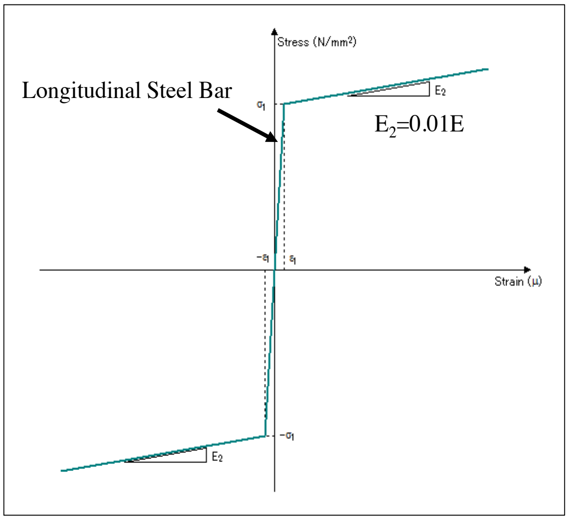


Fig. 6. Stress-Strain Curve of Concrete

Fig. 7. Stress-Strain Curve of Longitudinal Steel Bar

Similarly, as shown in Fig. 8 (f) and Fig. 9 (f), the analysis results of Type 4 of 0.1-scale model, which used D6 longitudinal steel bars, show the discrepancy in shape of hysteresis loops compared to experiment results. On the other hand, as shown in Fig. 8 (e) and Fig. 9 (e), the analysis results of Type 3 of 0.1-scale models, which used D3 longitudinal steel bars, are comparable with experiment results in not only the peak strength, but also energy absorption. A slight overestimation of the post-peak strength is due to the occurrence of localizing failure at the column base in experiment tests. Therefore, it can be argued that the discrepancy that is observed as mentioned above is due to the difference of the bond behavior between longitudinal steel bars and concrete, and therefore, the energy absorption of scaled RC column model would be significantly affected by the difference of shape of steel bar ribs.

Fig. 8 (c), (d) and Fig. 9 (c), (d) show hysteresis curves of Type 1 and Type 2 of 0.2-scale models, whose longitudinal steel bars are D6. As shown in Figs. 8 (c), (d) and Figs. 9 (c), (d), although the analytical results are comparable in hysteresis curves with experiment results, the discrepancy in this relationship is observed. It is seen that the shape of hysteresis curves of the 0.2-scale shows narrow loops in the experiment compared to the analysis results, and therefore the analysis results of 0.2-scale models overestimate energy absorption. This overestimation shows clear differences between analysis results and experiment results, and it may be concluded that this is due to the use of assumption of the perfect bond between longitudinal steel bars and concrete.

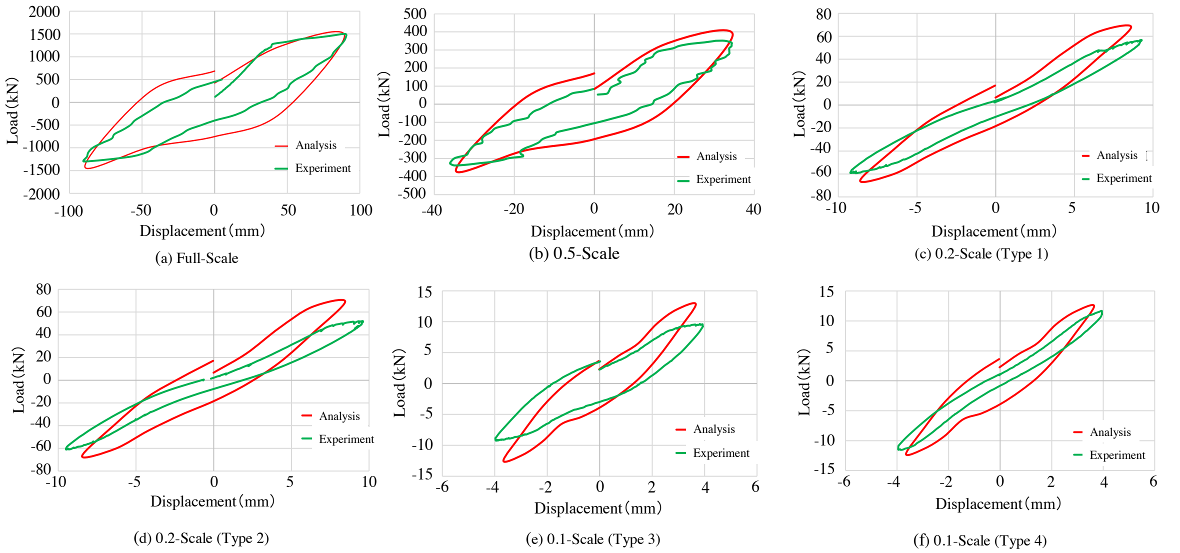


Fig. 8. $\pm 2.0\delta_y$

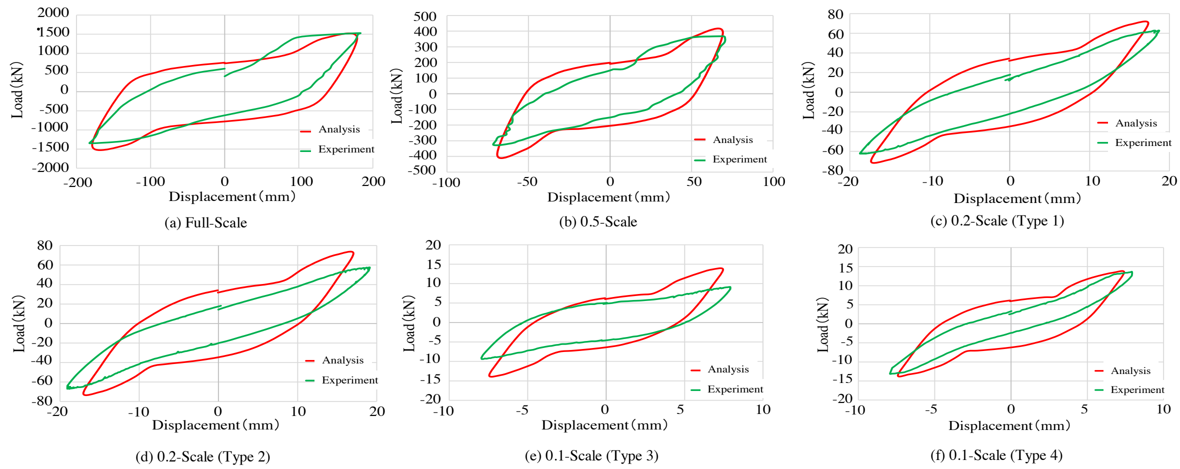


Fig. 9. $\pm 4.0\delta_y$

Similarly, as shown in Fig. 8 (f) and Fig. 9 (f), the analysis results of Type 4 of 0.1-scale model, which used D6 longitudinal steel bars, show the discrepancy in shape of hysteresis loops compared to experiment results. On the other hand, as shown in Fig. 8 (e) and Fig. 9 (e), the analysis results of Type 3 of 0.1-scale models, which used D3 longitudinal steel bars, are comparable with experiment results in not only the peak strength, but also energy absorption. A slight overestimation of the post-peak strength is due to the occurrence of localizing failure at the column base in experiment tests. Therefore, it can be argued that the discrepancy that is observed as mentioned above is due to the difference of the bond behavior between longitudinal steel bars and concrete, and therefore, the energy absorption of scaled RC column model would be significantly affected by the difference of shape of steel bar ribs

5. Conclusions

This study analyses full-, 0.5-, 0.2-, and 0.1-scale RC columns models using fiber model analyses to investigate the bond behavior analytically. Validity of the analysis was determined by comparing experimental results of full- and 0.5-scale model, which may behave perfect bond between longitudinal steel bars and concrete. Fiber model analysis results agree well with the full- and 0.5-scale model, and therefore it could be said that large-scaled models behave the perfect bond. Although results of 0.1-scale models, which is scaled correctly for not only steel bar radius, but also steel bar ribs, are capable to full- and 0.5scale model, analytical results of 0.2- and 0.1-scale model with different steel bar ribs shape, which are spiral ribs, seem to be less agreements. Therefore, it can be concluded that one of the causes of shortcomings in small-scale models is the difference of bond behavior between longitudinal steel bars and concrete.

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